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Economic evaluation for cooling and ventilation of medicine storage warehouses utilizing wind catchers

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ABSTRACT

Renewable energy consumption has become a dominant issue in many countries because of environmental crisis, pollution, climate change and increased costs of non-renewable sources like fossil fuels. Because of global warming and energy prices designers are refocusing on the low carbon credentials of new equivalents. In this context, the main target of the proposed study is to present a new innovative method of cooling the non-refrigerator medicine storage warehouses in order to minimize energy costs and environmental hazards for the city of Yazd in Iran. For this purpose, warehouses with absorption chillers, underground warehouses, and underground warehouses including wind catchers have been analyzed. Then, the equivalent uniform annual cost (EUAC) method was applied for evaluating the costs of the three alternative systems. The results of this study show that the use of wind catcher is far more economical than the absorption chiller cooling system. Moreover, it is concluded that the construction of an underground warehouse with a wind catcher is the most economical option for the storage of medicines than the other warehouses in this case study.

Contents

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1. Introduction

Industrial development caused humans to extend their destruction domain in nature. The outcome of this problem is contamination of soil and water and air pollution, which are progressively increasing. So, we are facing two major crises such as environmental and energy issues [1]. A major portion of energy consumption belongs to residential and commercial buildings for cooling and heating purposes. In order to choose the best alternative efficient system for buildings, different renewable sources of energy should be considered. Commercial and residential buildings have a great impact on energy consumption and environmental pollution. Buildings usually consume 35–40% of the primary energy, 30–40% of all raw materials used, 15–20% of all water used, and 10% of land use. Annually, staggering 3 billion tons of raw materials are used for building activities worldwide [2,3]. Buildings pollute the environment especially in big cities in many countries due to almost 35–40% of all greenhouse gas emissions, 30–35% of all solid waste generation, and about 20% of water effluents [2,4]. In Iran, consumption of energy in the building sector for cooling and ventilation is about 40%. There is a big demand to reduce this amount of consumption in order to achieve reduced pollution in the environment [5–7]. Suitable methods to resolve the present issues of the existing buildings are required because it is not possible to move them [2]. In this study, a new innovative method of cooling the non-refrigerator medicine storage warehouses is introduced for the city of Yazd in Iran using wind catchers. To examine the efficiency of the method, warehouses with absorption chillers, underground warehouses, and underground warehouses including wind catchers have been compared.

The main objectives in sustainable building design are to lower the energy consumption and also the life-cycle costs of the building. By lowering of the energy demand, the performance of the buildings would be improved considerably [8]. Creativity in the design of the buildings is a key step in order to achieve sustainable buildings with less consumption of energy. After removing of the subsidies by the government, the cost of fuel consumption to provide the proper temperature for keeping the medicines in a warehouse especially in the summer has increased rapidly due to the high consumption of absorbing chillers. The purpose of this study is to analyze the feasibility for the construction of wind catchers in the underground warehouses. It seems if we could provide the proper temperature for maintaining medicines by using renewable energy sources such as wind and also using thermal variation of the underground warehouse, we can reduce unnecessary costs. Energy consumption has become a dominant issue in many countries because of environmental crisis, pollution, climate change and increased costs of fossil fuels. Moreover, the unit energy prices have risen so it is important to find alternative cheaper and environment-friendly resources of energy with low carbon generation.

Spanaki et al. [9] designed a proper roof pond for passive cooling system, and then introduced the advantages and disadvantages of ponds as well as the design considerations. The conventional and intelligent control systems of the green concept for cooling and ventilation of buildings were discussed in order to provide free energy [10–13]. Saadatian et al. [14] reviewed wind catchers technology in order to provide space cooling and ventilation. A comprehensive list of phase change materials (PCMs) which are being used and can be used for free cooling of buildings was prepared [15,16]. The passive solar technologies for space heating and cooling were discussed and their advantages and limitations were highlighted; also, the relative efficiencies and applications of the various technologies were presented [17,18]. Sadineni et al. [19] discussed passive building energy savings in building envelope components. Pacheo et al. [20] reviewed energy efficiency of buildings, which is useful for residential buildings.

The rest of this paper is structured as follows: Section 2 describes wind catchers thoroughly. Geographical characteristics are discussed in Section 3. In Section 4, methodology is discussed. In Section 5, case study of three different designs is presented. Economic evaluation is discussed is Section 6. Finally, conclusions are drawn in Section 7.

2. Wind catchers

One of the old natural methods of air conditioning for buildings is using a wind catcher, which uses wind energy for the cooling process and makes pleasant air flow in the rooms, the hall and the basement of the buildings as well as warehouses. Wind catchers are tall towers which are built on the roofs of the houses with different forms in the central and the southern cities of Iran. As a matter of fact, using wind catchers has been common in Iran especially in the desert areas for many years. The wind catchers are usually found in different shapes, namely, they are one-sided, two-sided, four-sided and eight-sided. The shapes of the wind catcher have different designs. In Yazd city, located in arid central part of Iran, all the existing wind catchers are tall four-sided or eight-sided chimney shapes. In contrast, in Maybod city which is located near Yazd city at a distance of 50 km, the wind catchers are short and with only one-side chimney shape. People in Maybod had to build the wind catchers in the opposite direction of dust wind and in the direction of favorable wind. Since Yazd city is located between two mountains, desert wind is less strong and the taller wind catchers can be constructed. In general, the one-sided wind catchers are usually short but the four-sided and eight-sided wind catchers are taller. As an illustration, the taller wind catchers are built in eight-sided shape in order to have high stability against wind pressure. Generally, as long as the wind blows, the wind catcher pushes the interior warm air outside the building. Wind catchers are designed according to wind speed and wind direction of a specific region to achieve better performance.

Wind catchers have been used in buildings in most of the Middle Eastern countries for many centuries and they are known as Bawdgir in Iran [21–24]. They were constructed, traditionally, from wood-reinforced masonry with clay and sun-dried clay bricks. The height of the wind catchers are between 2 and 20 m above the building roof. Clearly, taller towers capture winds at higher speeds and less dust [21,24–26]. Fig. 1 shows a typical four-sided wind catcher in a garden (Khan Garden) close to the city of Yazd. Among the country's famous wind towers are Dowlatabad garden wind catcher, the historical Borujerdi house's tower and the Abbasian Badgir in Kashan [27].

Most wind catchers in warm dry regions were used to help balance humidity inside the structure. In many buildings in desert areas, the wind towers were built on top of a lavabo

Fig. 1. A typical wind catcher located in the city of Yazd.

(Howzkhaneh) to facilitate humidity required for a summer courtyard. The wind catchers are important elements in traditional Iranian architecture, providing natural air-conditioning in hot, dry and humid climates for thousands of years. These towers were built not only on ordinary houses but also on top of water cisterns (Ab-anbar) [28,29] as a natural refrigerator system to provide cold water for drinking.

Recently, much attention has been drawn by Iranian researchers to investigate the performance of wind catchers. Montazeri [30] using experimental wind tunnel, smoke visualization testing and computational fluid dynamic (CFD) examined the ventilation performance of wind catchers with different numbers of openings. His results indicated that the number of openings is a major parameter in the performance of wind catcher systems. Kalantar [31] conducted experimental examination and numerical simulation for investigating the cooling performance of wind catchers in Yazd in Iran. The most important result demonstrated that evaporative cooling is so efficient in a hot and dry region such as the city of Yazd that the temperature declines significantly, in case of equipping the wind towers with the water vaporization system. Bahadori et al. [32] evaluated the performance of two new designs of wind catchers and compared them with a conventional wind catcher in the city of Yazd. The two new designs of wind catchers were: one with a wetted column and the other one with wetted surfaces. Their obtained results showed that both new designs, with the air leaving the towers at a much lower temperature and a higher relative humidity than the ambient air, perform better than the conventional wind catcher.

Kazemi Esfeh et al. [33] utilized the smoke visualization approach to investigate the performance of several kinds of one-sided wind catcher models with flat, inclined or steep and curved roofs. The achieved results indicated that the wind catcher with a curved roof shows premier ventilation performance in comparison to the other two types.

In spite of some studies examined for the performance of wind catchers, optimization methods of warehouse design for cooling and ventilation of non-refrigerating medicines have not been studied yet. Therefore, to produce a more energy-efficient warehouse, this paper introduces a new innovative method of saving energy for cooling and ventilating warehouses.

3. Geographical characteristics

The case study is about the assessment of using wind catchers and also thermal variation of underground warehouse for storage of non-refrigerator medicines in the city of Yazd in the central part of Iran. Based upon the international pharmaceuticals regulation, principles of optimum conditions for storing of non-refrigerator medicines should be designed with appropriate temperature conditions and dry ventilation. Accordingly, the best temperature for the storage of non-refrigerator medicines is 15–30 °C [34]. For this research work, we analyze Yazd climate and the warehouse properties in order to store non-refrigerator medicines.

3.1. Yazd city description

Yazd province with an area of 131,575 km^2 is located in the central part of Iran. The city of Yazd, the capital of Yazd province, is located at 31°90′ N and 54°37′ E, and its altitude is 1230 m above mean sea level (Fig. 2). Yazd enjoys hot and dry weather conditions and the fluctuations of temperatures between summer and winter and through days and night are high and variable. Characteristically the weather includes two seasons, long summer from March to October and short winter from November to February.

During the summer, hot and dry air is dominant across the region. The evaporation rate is too high along with water deficiency. Humidity is also very low. However, the wind blows continuously in spring and summer in northwest prevailing direction [35]. This increases the water consumption use of plants more and more. Water scarcity and high consumption use of plants and trees has created such a condition in Yazd province that there are few agricultural activities.

Five years' measured ambient temperature in Yazd city shows the average ambient air temperature of 18.9 °C in the warm seasons. The average daytime temperature is around 30 °C. Furthermore, the difference between day and night temperatures is about 12 °C. The average annual relative humidity is 31% and the average of total sunshine duration is about 3223 h/year. The overall average of annual rainfall is less than 50 mm.

Table 1 illustrates the main meteorological parameters during (2007–2012) for the city of Yazd measured at Yazd meteorological station [36]. Generally, the best temperature condition in the warehouse for non-glacial medicines is between 15 and 30 °C [34]. Based on Table 1, by reducing temperature up to 10 °C during the warm season, we can provide appropriate storage conditions for the non-refrigerating medicines. Therefore, temperature reduction can be compensated by the use of natural wind catcher and temperature difference of the underground condition. As a matter

Fig. 2. Location of Yazd city on the map of Iran (Yazd province is shown in highlight).

Table 1
The main meteorological parameters during (2007–2012) for the city of Yazd.

Month	Total rainfall (mm)	Temperature (°C)			Relative humidity (%)	Sunshine duration (hours)
		Minimum	Average	Maximum		
Jan	12.1	0.0	5.9	12.3	54	190.3
Feb	4.8	1.9	8.7	15.5	44	210.6
Mar	10.1	6.7	13.5	20.3	38	218.9
Apr	4.4	12.4	19.4	26.5	33	242.9
May	3.5	17.4	24.7	32.1	26	300.7
Jun	0.6	22.2	30.0	37.7	18	343.5
Jul	0.1	24.3	31.9	39.4	18	345.7
Aug	0.0	21.9	30.0	38.0	18	345.0
Sep	0.0	17.5	25.9	34.3	19	316.0
Oct	1.1	11.3	19.4	27.6	27	286.4
Nov	3.4	4.9	12.4	19.9	39	224.2
Dec	9.7	0.6	7.5	14.3	50	199.0

of fact, it is possible to have higher temperature in the warm season for upcoming years which is hard to predict, and there is no guarantee for the maintenance of the desired temperature in the warehouse. But there should be an additional emergency cooling system equipment in order to keep the warehouse temperature in the desired condition. Since the maximum temperature belongs to the months of June, July and August, reduction of warehouse temperature to maintain the best conditions for non-glacial medicines should mainly be considered for these months.

According to the previous surveys [37–42], a wind catcher in low relative humidity conditions (i.e., between 10% and 30%) reduces temperature between 8 °C and 16 °C while in high relative humidity conditions (i.e., between 65% and 70%) it decreases temperature between 4 and 5 °C. As illustrated in Table 1, the maximum ambient temperature happens in June, July and August. The maximum temperature to keep non-refrigerating medicines is equal to 30 °C. Therefore, according to low level of relative humidity in Yazd and temperature difference of the warmest months of the year, reduction of ambient temperature up to appropriate range for keeping medicine is possible with using warehouses. Also, past study has shown that the temperature difference in the basement can provide this level of temperature reduction [20].

4. Methodology

In order to perform economic evaluation, the amount of heat loss of the warehouse and wind catcher should be calculated. The amount of heat losses from a wall and its input and output energy is calculated using the following equation [35]:

$$Q = UA(T_o - T_i) \tag{1}$$

where Q is the amount of heat loss (kcal/h) and A is the area of the wall, U is the overall heat transfer coefficient, T_o is the temperature of the outer layer and T_i is the temperature of the inner layer. The overall heat transfer coefficient (U) is calculated as follows [35]:

$$U = \frac{1}{1/h_i + \sum_{i=1}^{n} R_i + 1/h_o} \tag{2}$$

where R_i is the thermal resistance of the different layers of the wall that is obtained from the following formula [35]:

$$R_i = x_i/k_i \tag{3}$$

x_i is the wall thickness, k_i is the wall conduction coefficient, $1/h_i$ is the convective resistance of thin air layer on the inner wall of the warehouse and $1/h_o$ is the convection resistance of thin air layer on the outer wall of the warehouse. In case of using different surfaces, the value of h near each surface is not similar to the other surfaces; thus, it should be estimated separately for each surface. The amount of h for very smooth surfaces can be obtained from the following formula [35,43]:

$$h = 1.4 + 0.28\ V \tag{4}$$

the value of h for surfaces of wood or smooth plaster is calculated from the following equation [35]:

$$h = 1.6 + 0.3\ V \tag{5}$$

Also, for surfaces of concrete and smooth brick, h is obtained as follows [35]:

$$h = 2 + 0.4\ V \tag{6}$$

For rough surfaces, h can be calculated using the following equation [35]:

$$h = 2.1 + 0.5\ V \tag{7}$$

In the above relations, V is the air velocity near and on the wall in terms of miles per hour. The following formula is used for calculating the amount of the penetration air [35]:

$$q_p = \upsilon n \tag{8}$$

where q_p is the volume of air penetration, υ is the volume of room or location and n is the number of air exchange per hour in the room.

The amount of Q due to air penetration is calculated by the following formula [20,21]:

$$Q = q_p \times 1.2 \times 0.24(T_o - T_i) \tag{9}$$

The output volume flow rate of the wind catcher, q (m^3/h), is obtained by the following formula [34,44]:

$$q = VA \tag{10}$$

where V is the air velocity in the outlet and A is the area of wind catcher exit.

5. Case study

The considered ground level warehouse has length, width and height of 50, 14 and 10 m, respectively. The walls are made of clay bricks and windows are simple with a steel frame. The doors are made of steel with 30 mm thickness. There are six windows, each 5 m in length and 1.5 m in width, to supply the warehouse with natural light. It also has an entrance door 4 m × 6 m made of a steel sheet. Majority of the buildings in the area are made of clay bricks, because this construction material is popular and cheap. The layers used in the wall of the warehouse shown in Fig. 3 from outside to inside include: 3 cm of mortar cement, 3 cm of stone thumb, 30 cm of clay bricks, 1.5 cm plaster and 1 cm of gypsum. Three different designs were evaluated for this study:

- Ground level warehouse with absorption chiller;
- Underground warehouse;
- Underground warehouse with wind watcher.

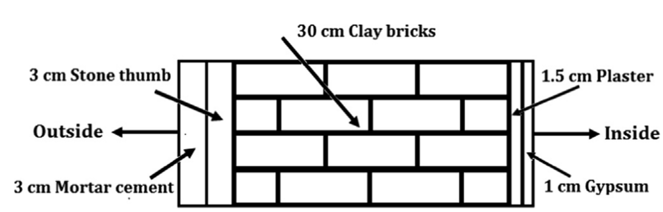

Fig. 3. The layers of ground level warehouse.

Table 2
The values of conduction heat transfer coefficient (k) and thickness (x) of the layers used in the wall of the warehouse.

Material	Mortar cement	Stone thumbs	Clay bricks	Plaster	Gypsum
k (kcal/m^2 h °C)	1.2	1.0	0.35	0.6	0.6
x (cm)	3.0	3.0	30.0	1.5	1.0

The conduction heat transfer coefficient (k) and the thickness (x) of different materials, used as layers in the wall of the warehouse, are presented in Table 2.

By considering the average wind speed in the city of Yazd equals to 10 mile/h or 1.8 m/s and using heat transfer coefficients (k) and density (ρ) [35], plus using Eqs. (1)–(10), the amount of heat losses for the three different cases of warehouse with absorption chiller system, underground warehouse and underground warehouse with wind catcher are calculated and expressed separately in the following sub-sections.

5.1. Ground level warehouse with absorption chiller

For cooling of the mentioned ordinary warehouse in the pharmaceutical industry, properties of a 20 years old absorbing chiller with 100 t cooling capacity were used. The chiller was purchased for 100 million IRR (IRR = Iranian Rials; \$1 = IRR 33000). It contains a 5.5 kW electro-pump whose main source of energy is natural gas. When the chiller is working, the boiler consumes 200 m^3/h of natural gas. The cold water of this chiller is transported via 22 kW electro-pump to the air-handling units. The 3 air-handling units with an average power of 8 kW provide cool air to the warehouse. The cost of a branch for a 1 t absorption chiller is about 100,000,000 IRR and the annual operation and maintenance costs of the absorption chiller is considered to be 10,000,000 IRR. In addition, the initial investment to produce steam is 120,000,000 IRR and the annual operation and maintenance cost of the boiler is 5,000,000 IRR. Considering the properties of the warehouse, the following calculation process was conducted to estimate the amount of heat loss for the warehouse including absorbing chiller.

5.1.1. Calculation of U for sidewalls:

In order to calculate the amount of heat losses from the sidewalls of the warehouse, both convection and conduction heat transfers should be considered. Convection heat transfer from inside and outside of the warehouse walls are estimated using the Eqs. (4) and (6) as follows:

$$h_i = 1.4 + 0.28\,V = 1.4 + 0.28 \times 0 = 1.4\ (\mathrm{BTU/ft^2\ h\ F}) = 6.83\ (\mathrm{kcal/m^2\ h\ ^\circ C}) \tag{11}$$

$$h_o = 2.0 + 0.4\,V = 2.0 + 0.4 \times 10 = 6.0\ (\mathrm{BTU/ft^2\ h\ F}) = 29.8 (\mathrm{kcal/m^2 h ^\circ C}) \tag{12}$$

Using the calculated convection heat transfer coefficients and the parameters presented in Table 2, the overall heat transfer coefficient (Eq. (2)) is calculated as:

$$U = \frac{1}{(1/6.83)+(0.01/0.6)+(0.015/0.6)+(0.3/0.35)+(0.03/1)+(0.03/1.2)+(1/29.28)} = 0.87\ (\mathrm{kcal}/m^2\ \mathrm{h}\ ^\circ C) \tag{13}$$

5.1.2. Calculation of U for roof:

As listed in Table 3, the roof is made of concrete with asphalt, coating and 5 cm insulation with overall heat transfer coefficient of 0.6 kcal/m^2 h °C.

Table 3
Coefficient values for roofs.

Roof type	**U** coefficient $\left(\frac{\mathrm{kcal}}{\mathrm{m^2\ h\ ^\circ C^1}}\right)$
15 cm thick concrete with asphalt	3.1
15 cm thick concrete with asphalt and coating	2.7
15 cm thick concrete with asphalt and 2.5 cm insulation	1.20
15 cm thick concrete with asphalt, coating and 2.5 cm insulation	1.00
15 cm thick concrete with asphalt and 5 cm insulation	0.65
15 cm thick concrete with asphalt, coating and 5 cm insulation	0.60
15 cm thick brick block	2.40
15 cm thick brick block with coating	2.20
15 cm thick brick block with 2.5 cm insulation	1.00
15 cm thick brick block with 5 cm insulation	0.90
15 cm thick brick block with 5 cm insulation and coating	0.60

Table 4
Coefficient values for doors and windows.

Material	***U*** coefficient $\left(\frac{\mathrm{kcal}}{\mathrm{m^2\ h^\circ\ C^1}}\right)$
38 mm thick external wood door	2.00
25 mm thick external wood door	2.50
Iron door	5.00
Door with 1/2 glass	4.00
Internal door	2.00
External wood window- regular glass	4.50
External wood window- two layer glass (6 mm layer)	3.10
External wood window- two layer glass (12 mm layer)	2.80
External iron window- regular glass	5.00
External iron window- two layer glass (6 mm layer)	3.40
External iron window- two layer glass (12 mm layer)	3.10

Table 5
Heat loss of warehouse including absorbing chiller.

Title	n	A (m^2)	ΔT (°C)	U (Kcal/m^2 h °C)	Q (Kcal/h)
North side wall	–	477.5	10	0.87	4154.25
South side wall	–	477.5	10	0.87	4154.25
East side wall	–	116	10	0.87	1009.20
West side wall	–	140	10	0.87	1218.00
Ceiling	–	700	10	0.60	4200.00
Windows	–	45	10	30.00	13500.00
Door	–	24	10	5.00	1200.00
Air penetration	1	–	10	–	20160.00
Q_{total}					49595.70

5.1.3. Calculation of U for door:

The door is made of iron with dimension of 4 m × 6 m. As shown in Table 4, the overall heat transfer coefficient of the door is equal to 5 kcal/m^2 h °C.

5.1.4. Calculation of U for windows:

The dimensions of each considered window is 5 m × 1.5 m. As seen in Table 4, the overall heat transfer for each external iron window with regular glass is equal to 5 kcal/m^2 h °C.

5.1.5. Calculation of Q by air penetration:

The number of air exchange per hour is assumed to be 1 then the volume of air penetration using Eq. (8) is

$$q_p = \upsilon n = (14 \times 50 \times 10) \times 1 = 7000\ \mathrm{m^3/h} \tag{14}$$

The total heat rate, Q, due to air penetration is obtained using Eq. (9) as follows:

$$Q = 7000 \times 1.2 \times 0.24 \times (30-20) = 20160\ \text{kcal/h} \tag{15}$$

In Table 5, the amount of the overall heat transfer coefficient and the total amount of heat loss for each part of the warehouse are listed.

5.2. Underground warehouse

If the warehouse is built under the ground instead of on the ground surface, the amount of heat loss decreases slightly. Thermal variation of underground and the ground surface was studied and findings show that the average thermal variation between underground and the ground surface is 6 °C. The layers used in the wall of the basement from outside to inside include 23 cm of clay bricks, 2 cm of cement plaster, 3 mm of insulation, 10 cm of clay bricks, 1.5 cm gypsum and clay mortar and 1 cm of ceramic tile. These different layers are illustrated in Fig. 4. In Table 6, the conduction coefficient (k) and the thickness (x) of different materials utilized as layers in the wall of the basement are given.

5.2.1. Calculation of U for sidewalls:

For calculating the amount of heat loss from the sidewalls of the warehouse, both convection and conduction heat transfers should be considered. Convection heat transfer from inside and outside of the underground warehouse can be estimated using Eqs. (4) and (6):

$$h_i = 1.4+0.28\ V = 1.4+\ 0.28 \times 0 = 1.4(\text{BTU/ft}^2\ \text{h F}) = 6.83(\text{kcal/m}^2\ \text{h °C}) \tag{16}$$

$$h_o = 2.0+0.4\ V = 2.0+0.4 \times 0 = 2.0(\text{BTU/ft}^2\ \text{h F}) = 9.76(\text{kcal/m}^2\ \text{h C}) \tag{17}$$

Using the determined convection heat transfer coefficients and the values of parameters presented in Table 6, the overall heat transfer coefficient (Eq. (2)) is calculated as follows:

$$U = \frac{1}{(1/6.83)+(0.01/0.6)+(0.015/0.6)+(0.1/0.35)+(0.003/0.2)+(0.02/1)+(0.23/0.35)+(1/9.76)} = 0.77(\text{kcal}/m^2\ \text{h °}C) \tag{18}$$

The values of U for the ceiling and door of the underground warehouse are same as for the warehouse. U and Q values for different parts of the underground warehouse are tabulated in Table 7.

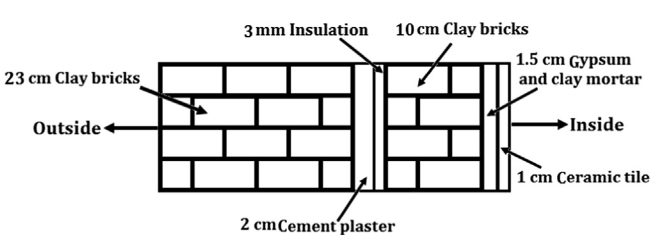

Fig. 4. Layers of the wall used for the basement.

5.2.2. Calculation of U for roof:

The roof is made of concrete along with 5 cm insulation and according to Table 3, the overall heat transfer coefficient of the roof is equal to 0.6 kcal/m^2 h °C.

5.2.3. Calculation of U for door:

The door is made of iron and the dimension is 4 m × 6 m. According to Table 4, the overall heat transfer coefficient of the door is equal to 5 kcal/m^2 h °C. Now the total amount of Q can be calculated. The obtained values are presented in Table 7.

Thus, if a warehouse is to be built under the ground, the amount of Q for the whole building decreases from 49595.70 to 8834.7 kcal/h. Therefore, the saved amount of Q is calculated as follows:

$$Q = 49595.70 - 8834.7 = 40761.0\ \text{kcal/h} \tag{19}$$

5.3. Underground warehouse with wind watcher

At this stage, we add a wind catcher to the warehouse and do the related calculations. The height of the wind catcher is 14 m and the width of its square cross-section is equal to 1.5 m; therefore, the cross-section area of the wind catcher is equal to 2.25 m^2. In addition, 10 m of the total height of the wind catcher is designed inside the warehouse and 4 m is outside. The average ambient temperature is 30 °C and the average temperature inside the wind catcher is considered to be 22 °C. The output volumetric flow rate of the wind catcher using Eq. (10) is

$$q = \text{V}.A = 1.8 \times 2.25 = 4.05\ \text{m}^3/s = 14580\ \text{m}^3/\text{h} \tag{20}$$

Now we can estimate the value of Q using Eq. (9)

$$Q = \text{q} \times 1.2 \times 0.24 \times (T_o - T_i) = 14580 \times 1.2 \times 0.24 \times (30-22) = 33592.3\ \text{kcal/h} \tag{21}$$

Thus, the rate of heat loss compensated by the wind catcher is 33592.3 kcal/h. Now we can estimate the amount of heat loss from different parts of the wind catcher. The calculated values of U and also Q for different parts of the wind catcher are shown in Table 8.

Table 7
Heat loss in the underground warehouse.

Material	A (m^2)	ΔT (°C)	U (Kcal/m^2 h °C)	Q(Kcal/h)
North side wall	477.5	6	0.77	2206.0
South side wall	477.5	6	0.77	220.0
East side wall	116	6	0.77	535.9
West side wall	140	6	0.77	646.8
Ceiling	700	6	0.60	2520.0
Door	24	6	5.00	720.0
Q_{total}				8834.7

Table 6
The values of conduction coefficient (k) and thickness (x) of the layers utilized in the wall of the basement.

Material	Clay bricks	Cement plaster	Insulation	Clay bricks	Gypsum and clay mortar	Ceramic tile
k (kcal/m^2 h °C)	0.35	1.0	0.2	0.35	0.6	0.5
x (cm)	23.0	2.0	0.3	10.0	1.5	1.0

Table 8
Heat loss for the warehouse with a wind catcher.

Title	A (m^2)	ΔT (°C)	U (Kcal/m^2 h °C)	Q (Kcal/h)
Space inside the storage and the wind catcher	60.00	8	2.387	1145.70
Space inside and outside the wind catcher	24.00	8	2.766	531.00
Wind catcher roof	2.25	8	1.264	22.76
Q_{total}				1699.40

In Table 8, the total amount of heat loss from the wind catcher is calculated as

$$Q = 1699.4 \text{ kcal/h} \tag{22}$$

Considering the heat loss in the wind catcher, the amount of energy loss of the warehouse (while using the wind catcher) is equal to

$$Q = 49595.70 - 33592.3 + 1699.4 = 17702.8 \text{ kcal/h} \tag{23}$$

6. Economic evaluation of warehouse with chiller and wind catcher

The method of equivalent uniform annual cost (EUAC) for economic analysis of projects is used here for decision making in different warehouses. It is one of the techniques in which revenues and expenses are converted into uniform annual received or paid.

EUAC is the average annual cost of owning and operating a project over its entire life time. It is the 'payment' required to fund the life cycle cost (LCC) over the service life of the project. The alternatives must be mutually exclusive and repeatedly renewed up to the duration of the longest-lived alternative. When EUAC gets a value of zero or greater than zero, the project would be economically feasible or acceptable. But, if it gets a negative value, the project would not be acceptable. By comparing some alternatives, the one with higher value of EUAC would be considered as the better option.

One of the advantages of this method is that we can easily compare projects with different useful life times. It is assumed that both projects have the same amount of benefits here:

$$\text{EUAC} = P(A/P, I\%, n) - SV(A/F, I\%, n) \tag{24}$$

Here, P is the initial capital, F is the future value, A is the uniform equal cost at the end of each period, n is the useful life time, SV is the salvage value and I stands for interest rate [43]. In order to compare the projects, EUAC of each project should be calculated. Then, the project with the least value of EUAC would be the best alternative choice.

6.1. Warehouse with absorption chiller

The useful life of the chillers is estimated to be 20 years while after 10 years the salvage value would be IRR 40,000,000 which would then decrease by IRR 5,000,000 every year. At the end of its useful life, its salvage value would be zero. MARR (minimum attractive rate of return) was considered to be 10% in all cases.

Annual operation and maintenance (O&M) cost of the chiller was estimated to be: EUAC $_{O\&M}$=15,000,000 IRR. Initial cost (P_1) of warehouse construction can be calculated as following since its total area is 700 m^2, and the cost of one square meter is 4,000,000 IRR:

$$P_1 = 4,000,000 \text{IRR}/\text{m}^2 \times 700 \text{ m}^2 = \text{IRR}2,800,000,000.$$

Initial total cost (P_2) of the chiller system including transportation and facility room and all other belongings is:

$$P_2 = \text{IRR } 320,000,000. \tag{25}$$

Therefore, total initial cost of the warehouse with the chiller is: $P = P_1 + P_2$ = IRR 3,120,000,000.

The total amount of power consumed, in case of utilizing the chiller, is the sum of the chiller's electro-pump power (5.5 kW), the power required to transfer the cold water by electro-pump to air handling (22 kW) and the power of 3 air-handling units (3 × 8 kW), which is obtained equal to 51.5 kW. Since the average cost of electricity in Iran is 430 IRR/kW h, the cost of electricity consumption would be 22,145 IRR/h. In addition, the value of natural gas price in Iran is 900 IRR/m^3, and gas consumption for the chiller is 200 m^3/h. Hence, the consumption of gas for the chiller would be 180,000 IRR/h. Chillers operate for 170 days per year, and also 17 h per day on an average. Therefore, the total annual cost of electricity and gas for the chillers would be 63,999,050 IRR and 520,200,000 IRR, respectively.

Total energy loss of the warehouse with a chiller is 49595.70 kcal/h. If the cost of rate of energy loss be 3 IRR per kcal/h, then its cost would be 148,787.1 IRR/h or 429,994,719 IRR/year. The life time (useful life) of the warehouse is considered to be 20 years; in addition, the salvage value of the warehouse is zero.

The total annual cost of electricity for the warehouse with absorption chiller, gas, and heat loss would be:

$$\begin{aligned}\text{EUAC} &= 15,000,000 + 63,999,050 + 520,200,000 + 429,994,719 \\ &= 1,029,193,769 \text{IRR/year}.\end{aligned} \tag{26}$$

Here, final EUAC of the warehouse with chiller would be:

$$\begin{aligned}&\text{EUAC}_{(\text{warehousewithchiller})} \\ &= 1,029,193,769 + 3,120,000,000(A/P, 10\%, 20) \\ &\quad - 0(A/\text{F}, 10\%, 20) \\ &= 1,395,668,969 \text{IRR/year}.\end{aligned} \tag{27}$$

6.2. Underground warehouse

The total heat loss for warehouse is equal to 8834.7 kcal/h and the annual cost is equivalent to 76,596,849 IRR/year. Annual operation and maintenance cost of the warehouse is 10,000,000 IRR/year. The total annual cost of the warehouse is 86,596,849 IRR/year. As a consequence, the initial cost of the warehouse is 3,850,000,000 IRR. The life time (useful life) of the warehouse is assumed to be 20 years; in addition, the salvage value of the warehouse is zero.

$$\begin{aligned}&\text{EUAC}_{(\text{Undergroundwarehouse})} \\ &= 86,596,849 + 3,850,000,000(A/P, 10\%, 20) - 0(A/\text{F}, 10\%, 20) \\ &= 538,817,849 \text{IRR/year}.\end{aligned} \tag{28}$$

6.3. Underground warehouse with wind catcher

The construction costs of wind catchers are 2,000,000 IRR/m^2 in Iran. The initial cost of the wind catcher was estimated to be 63,000,000 IRR, and also the total cost of a warehouse with a wind catcher was estimated to be 2,863,000,000 IRR. Annual operation and maintenance (O&M) cost of the wind catcher is estimated as: EUAC $_{O\&M}$=500,000 IRR/year.

The total heat loss of a warehouse with a wind catcher is 17702.8 kcal/h and the annual cost of the wind catcher is equivalent to 121,699,056 IRR/year.

If the cost of energy loss be 3 IRR per kcal/h, then its cost would be 53,108.4 IRR/h or 153,483,276 IRR/year. Salvage value of the wind catcher at the end of its useful life is zero. Now, the EUAC of the warehouse with a wind catcher can be calculated using Eq. (24) as:

$$\begin{aligned}&\text{EUAC}_{(\text{Warehousewithwindcatcher})} \\ &= 2,863,000,000(A/P, 10\%, 20) + 500,000\end{aligned}$$

Table 9
Cost of different warehouses.

	Equivalent uniform annual cost (IRR/Year)
Warehouse with absorption chiller	1,395,668,969
Underground warehouse	538,817,849
Underground warehouse including wind catcher	490,271,256

$$+153,483,276\text{–}0(A/\mathrm{F},10\%,50)$$
$$=490,271,256\,\mathrm{IRR/year} \quad (29)$$

Table 9 indicates that the equivalent uniform annual cost (EUAC) of warehouse system with absorption chiller is much higher than the underground warehouse with and without the wind catcher system.

Therefore, according to EUAC method whose results are presented in Table 9, the utilization of underground warehouses including wind catchers for medicine storage purpose in the city of Yazd is suggested as a more economically viable option.

7. Conclusions

In this research, the project of constructing a warehouse having absorbing chiller was compared economically with the project of constructing underground warehouses and underground warehouses with a wind catcher using the equivalent uniform annual cost (EUAC) method. The results indicated that the cost of the project for constructing a wind catcher in a warehouse is less than the cost of a warehouse having an absorbing chiller. Also, the project for constructing an underground warehouse was compared with the warehouse having an absorbing chiller system. The results show that the construction of an underground warehouse is more economical than the use of an absorbing chiller system. Consequently, constructing the wind catcher in the existing warehouse is more economical than using the chiller system. As long as companies wish to construct warehouses in order to store non-refrigerator medicines with the specifications imposed by the government, it is possible and economical to construct underground warehouses including wind catchers. This reduces costs and provides a sustainable energy base system for the region.

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